A Novel Controller Based 48-Pulse STATCOM for Reactive Power Compensation and Voltage Stabilization in High Voltage Applications

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Abstract—**These paper presents the dynamic operation of a novel control scheme for Static Synchronous Compensator (STATCOM) based on a new full model comprising a 48-pulse Gate Turn-Off (GTO) thyristor voltage source converter for combined reactive power compensation and voltage stabilization of the electric grid network. The novel controller for the STATCOM presented in this paper is based on a decoupled strategy using the direct and quadrature components of the STATCOM current. The complete digital simulation of the STATCOM within the power system is performed in the MATLAB/Simulink environment using the Power System Blockset (PSB). The STATCOM scheme and the electric grid network are modeled by specific electric blocks from the power system blockset, while the control system is modeled using Simulink. The performance of ±100 Mvar STATCOM connected to the 500-kV grid is evaluated. The proposed novel control scheme for the STATCOM is fully validated for both the capacitive and inductive modes of operation by digital simulation.**

Index Terms—**48-pulse GTO thyristor model STATCOM, novel decoupled control strategy, reactive compensation, voltage stabilization.**

I. INTRODUCTION

The advent of FACTS systems is giving rise to a new family of power electronic equipment for controlling and optimizing the dynamic performance of power system, e.g., STATCOM, SSSC, and UPFC[1].These Power electronic converters connected in parallel or in series with transmission lines bring the interaction between the compensating devices and the grid network, which is preferably studied by digital simulation. This paper deals with a novel cascaded multilevel converter model, which is a 48-pulse (three levels) GTO based STATCOM employing 4 × 12-pulse voltage source converter [4] is realized and employed to regulate voltage in high-voltage transmission system. Three basic techniques can be used for reducing the harmonics produced by the converter switching [8], [9], Harmonic neutralization using magnetic coupling (multipulse converter configurations), harmonic reduction using multilevel converter configurations and novel pulse-width modulation (PWM) switching techniques. For high-power applications with low distortion, the best option is the 48-pulse converter, scheme which ensures minimum power quality problems and reduced harmonic resonance conditions on the interconnected grid network.

II. OPERATION OF STATCOM

The basic STATCOM model consists of a step-down transformer with leakage reactance, a three-phase GTO VSI, and dc side capacitor. The ac voltage difference across this transformer leakage reactance produces reactive power exchange between the STATCOM and the power system at the point of interface [5] [6]. The STATCOM's main function is to regulate key bus voltage magnitude by dynamically absorbing or generating reactive power to the ac grid network, like a thyristor static compensator. The voltage provided by a voltage-source PWM inverter is always in quadrature to the STATCOM current.

The STATCOM device operation can be illustrated by the phasor diagrams shown in Fig. 1.

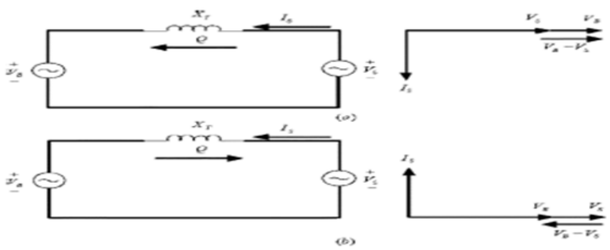

Fig.1. STATCOM operation (a) Inductive Mode

(b) Capacitive Mode

In steady-state operation and due to inverter losses, the bus voltage (VB) always leads the inverter ac voltage by a very small angle to supply the required small active power losses [2].

III. DIGITAL SIMULATION MODEL

A novel complete model using the 48-pulse digital simulation of the STATCOM within a power system is presented in this paper. The digital simulation is performed using the MATLAB / Simulink software environment and the Power System Blockset (PSB). The control process is based on a novel decoupled current control strategy using both the direct and quadrature current components of the STATCOM. The operation of the full STATCOM model is

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fully studied in both capacitive and inductive modes in a power transmission system and load excursion.

A. Power System Description

A ±100 Mvar STATCOM device is connected to the 500kV (L-L) grid network. Fig. 2 shows the single line diagram representing the STATCOM and the host sample grid network. The feeding network is represented by a thevenin equivalent at (bus B1) where the voltage source is

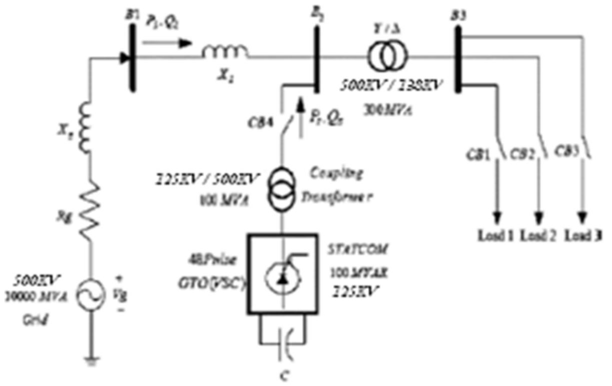

Fig. 2: Sample three-bus study system with the STATCOM located Bus at B2

represented by a 500*1.03 kV with 10000 MVA short circuit power level with an $\frac{X}{R}$ =8 followed by the transmission line connected to bus B2. The full system parameters are given in Table I.

The STATCOM device comprises the full 48-pulse voltage source converter-cascade model connected to the host electric grid network through the coupling transformer. The dc link voltage is provided by the capacitor C, which is charged from the ac network. The decoupled current control system ensures full dynamic regulation of the bus voltage (VB) and the dc link voltage . The 48-pulse VSC generates less harmonic distortion and, hence, reduces power quality problems in comparison to other converters such as (6, 12, and 24) pulse.

B. 48-Pulse Voltage Source GTO-Converter.

It consists of four three-phase, three-level inverters and four phase-shifting transformers. In the 48-pulse voltage source converter, the dc bus V_{dc} is connected to the four three-phase inverters. The four voltages generated by the inverters are applied to secondary windings of four zig-zag phase-shifting transformers connected in Y or Ä. The four transformer primary windings are connected in series, and the converter pulse patterns are phase shifted so that the four voltage fundamental components sum in phase on the primary side.

Using a symmetrical shift criterion, the 7.5° are provided in the following way: phase-shift winding with -3.75° on the two coupling transformers of one 24-pulse converter and +3.75° on the other two transformers of the second 24-pulse converter. The firing pulses need a phase-shift of +3.75°, respectively.

Three phase AC source	
Rated voltage	500*1.03[KV]
Frequency	60[Hz]
S.C Level	10000[MVA]
Base voltage	500[KV]
X/R	8
Transmission Line	
Resistance	0.05
Reactance	0.2
No.of phases	3
Length of line	200[km]
Power Transformer	
Nominal Power	300[MVA]
Frequency	60[Hz]
Prim.Voltage	500[KV]
Sec.Voltage	138[KV]
Magnetization Resist.	500
Magnetization React.	500
Three Phase Loads	
Load1	
Active Power	1[pu]
Reactive power	0.8[pu]
Load2	
Active Power	0.7[pu]
Reactive Power	0.5[pu]
Load3	
Active Power	0.6[pu]
Reactive Power	0.4[pu]

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ACEEE

STATCOM	
Primary Voltage	125[KV]
Secondary Voltage	25[KV]
Nominal Power	100MVAR
Frequency	60[Hz]
Eq.capacitance	8μF
Coupling Transformer	
Nominal Power	100MVA
Frequency	60[Hz]
Prim.Voltage	125[kv]
Secondary Voltage	230[kv]
GTO switches	
Snubber Resistance	1e5[ohm]
Snubber Cap.	inf
Internal resistance	1e-4[ohm]
No. of Bridge arms	3

The 48-pulse converter model comprises four identical 12-pulse GTO converters interlinked by four 12-pulse transformers with phase-shifted windings [9]. Fig. 3 depicts the schematic diagram of the 48-pulse VS-GTO converter model. The transformer connections and the necessary firing-pulse logics to get this final 48-pulse operation are modeled. The 48-pulse converter can be used in high-voltage high-power applications without the need for any ac filters due to its very low harmonic distortion content on the ac side. The output voltage have normal harmonics n=48r±1, where r=0,1,2,…, i.e., 47th, 49th, 95th,…, with typical magnitudes (1/47th,1/49th,1/95th…), respectively, with respect to the fundamental; on the dc side, the lower circulating dc current harmonic content is the 48th.

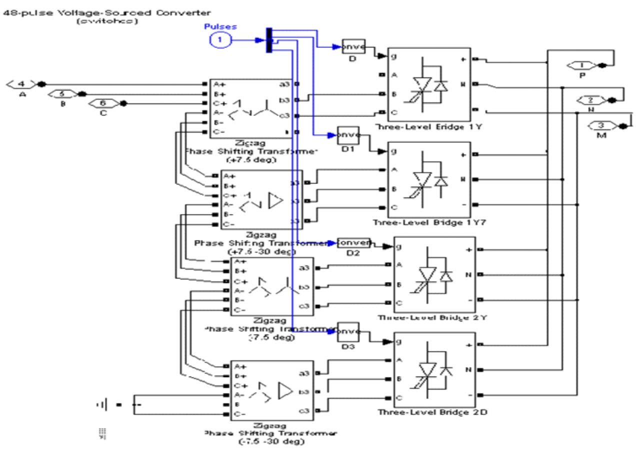

Fig. 3. Forty-eight-pulse GTO's voltage source converter

2nd 12-Pulse Converter: : It is shown in the second equation at the bottom of the previous page. The resultant output voltage generated by the second 12-pulse converter is

$$v_{ab12}(t)_2 = 2[V_{ab1}Sin(wt + 30^0) + V_{ab11}Sin(11wt + 15^0)$$

$$+V_{ab13}Sin(13wt + 75^0) + V_{ab23}Sin(23wt + 60^0)$$

$$+V_{ab25}Sin(25wt + 120^0) + \cdots \dots \dots \dots \dots \dots \dots \dots \dots .].$$

3rd 12-Pulse Converter: It is shown in the first equation at the bottom of the page. The resultant output voltage generated by the third 12-pulse converter is

$$v_{ab12}(t)_3 = 2[V_{ab1}Sin(wt + 30^0) + V_{ab11}Sin(11wt + 285^0)$$

$$+V_{ab13}Sin(13wt + 345^0) + V_{ab23}Sin(23wt + 240^0)$$

$$+V_{ab25}Sin(25wt + 300^0) + \cdots \dots \dots \dots \dots \dots \dots \dots \dots .].$$

4th 12-Pulse Converter: It is shown in the second equation at the bottom of the page. The resultant output voltage generated by the fourth 12-pulse converter is

$$v_{ab12}(t)_4 = 2[V_{ab1}Sin(wt + 30^0) + V_{ab11}Sin(11wt + 105^0)$$

$$+V_{ab13}Sin(13wt + 165^0) + V_{ab23}Sin(23wt + 240^0)$$

$$+V_{ab25}Sin(25wt + 300^0) + \cdots \dots \dots \dots \dots \dots \dots \dots \dots .].$$

These four identical 12-pulse converters provide shifted ac output voltages, described by (1)–(4), are added in series on the secondary windings of the transformers. The net 48-pulse ac total output voltage is given by

$$v_{ab48}(t) = V_{ab12}(t)_1 + V_{ab12}(t)_2 + V_{ab12}(t)_3 + V_{ab12}(t)_4$$

$$v_{ab48}(t) = 8[V_{ab1}Sin(wt + 30^0) + V_{ab47}Sin(47wt + 150^0)$$

$$+V_{ab49}Sin(49wt + 210^0) + V_{ab95}Sin(95wt + 330^0)$$

$$+V_{ab97}Sin(97wt + 30^0) + \cdots \dots \dots \dots \dots \dots \dots \dots \dots .].$$

The phase-shift pattern on each four 12-pulse converter cascade is as follows.

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1st 12-Pulse Converter: The resultant output voltage generated by the first 12-pulse converter is

$$v_{ab12}(t)_1 = 2[V_{ab1}Sin(wt+30^0) + V_{ab11}Sin(11wt + 195^0)$$

$$+V_{ab13}Sin(13wt+255^0) + V_{ab23}Sin(23wt+60^0)$$

$$+V_{ab25}Sin(25wt+120^0) + \cdots \ldots \ldots \ldots \ldots \ldots .]$$

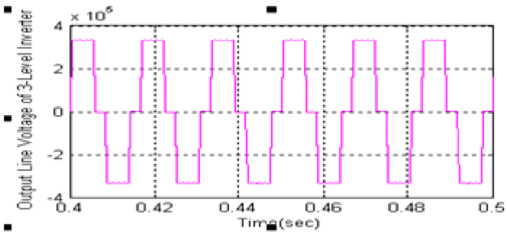

Fig.4 Three Level inverter output Voltage

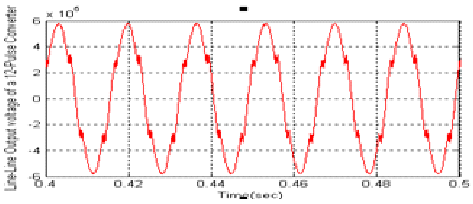

Fig5.Output line voltage of 12-Pulse VSC

Fig.4 & Fig.5 depicts line-to-line output voltage of the 3-level inverter and 12-pulse VSC based STATCOM .The line-to-neutral 48-pulse ac output voltage from the STATCOM model is expressed by

$$v_{ab48}(t) = 8/\sqrt{3}\sum_{n=1}^{\infty} V_{abn}\,Sin(nwt + 18.75^0 n - 18.75^0 i)$$

$$n = (48r \pm 1), r = 0,1,2, \ldots .$$

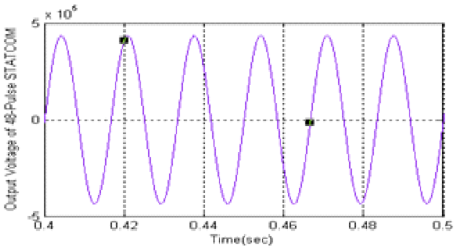

Fig. 6. 48-pulse converter output voltage.

Voltages $V_{bn48}(t)$and $V_{cn48}(t)$ have a similar near sinusoidal shape with a phase shifting of 120 and 240 , respectively, from phase a $V_{an48}(t)$. Fig. 6 depicts the net resultant 48-pulse line-to-line output voltage of the 48-pulse GTO-Converter scheme.

C. Decoupled Current Control System

The new decoupled control system is based on a full - decoupled current control strategy using both direct and quadrature current components of the STATCOM ac current. The decoupled control system is implemented as shown in Fig. 7. A phase locked loop (PLL) synchronizes on the positive sequence component of the three-phase terminal voltage at interface Bus 2. The output of the PLL is the angle (è) that used to measure the direct axis and quadrature axis component of the ac three-phase voltage and current. The outer regulation loop comprising the ac voltage regulator provides the reference current (Iqref) for the current regulator that is always in quadrature with the terminal voltage to control the reactive power. The voltage regulator is a proportional plus integral PI controller with KP=5 and Ki=0.09. The current regulator is also PI controller with KP=12 and Ki=0.09. The PLL system generates the basic synchronizing-signal that is the phase angle of the transmission system voltage Vs, è and the selected regulation-slope k determines the compensation behavior of the STATCOM device. To enhance the dynamic performance of the full 48-pulse STATCOM device model, a supplementary regulator loop is added using the dc capacitor voltage. The dc side capacitor voltage charge is chosen as the rate of the variation of this dc voltage. Thus, for a fixed selected short time interval Ät, the variation in the Vdc magnitude is measured, and any rapid change in this dc voltage is measured and if this $|\Delta V_{dc}|$ change is greater than a specified threshold K, the supplementary loop is activated. The main concept is to detect any rapid variation in the dc capacitor voltage.

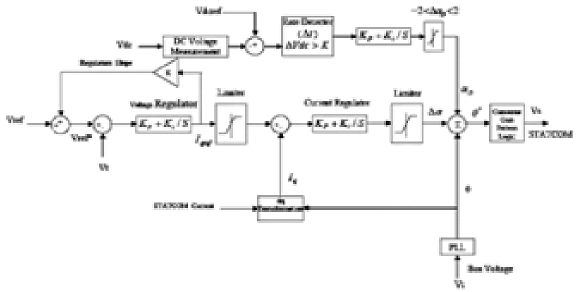

Fig.7. Novel STATCOM d-q decoupled current control system.

The strategy of a supplementary damping regulator is to correct the phase angle of the STATCOM device voltageθ, with respect to the positive or negative sign of this variation. If $\Delta V_{dc} >$, means the dc capacitor is charging very fast. This happens when the STATCOM converter voltage lag behind the ac system voltage; in this way, the converter absorbs a small amount of real power from the ac system to compensate for any internal losses and keep the capacitor voltage at the desired level. The same technique can be used to increase or decrease the capacitor voltage and, thus, the amplitude of the converter output voltage to control the var generation or absorption. This supplementary loop reduces ripple content in charging or discharging the capacitor and improves fast controllability of the STATCOM.

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IV. DYNAMIC PERFORMANCE OF THE STATCOM

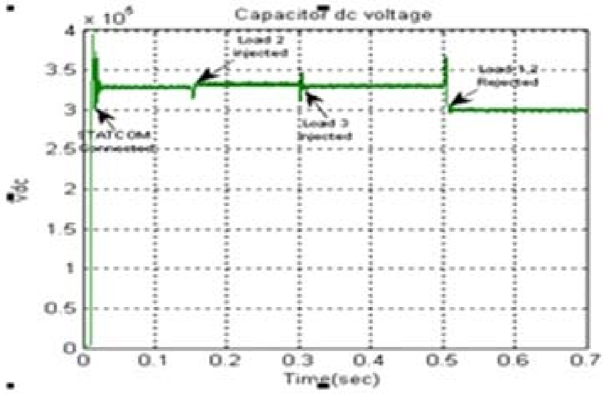
The sample study radial power system is subjected to load switching at bus B3. When starting, the source voltage is such that the STATCOM is inactive. It neither absorbs nor provides reactive power to the network. The network voltage V_g is 1.03 p.u. and only inductive load 1 with P=1pu and Q=0.8pu (at rated voltage) is connected at load bus B3, and the STATCOM connected B2 bus voltage is 1.055 pu for the uncompensated system and the transmitted real and reactive power are P=0.3pu and Q=0.6pu. The digital simulation results are given as shown in Fig. 8. The following load excursion sequence is tested.

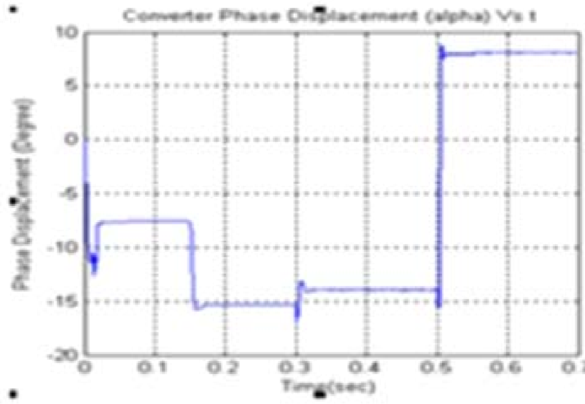
Step 1) t=0.01s—at this time, the static synchronous compensator STATCOM is switched and connected to the power system network by switching on the circuit breaker CB4. The STATCOM is now operating in the capacitive mode and injects about 0.275pu of reactive power into the ac power system, as shown in Fig. 8(d).The B2 bus voltage increased to 1.071 p.u. as shown in Fig. 8(e). The STATCOM draws 0.01 p.u. of real-active power from the network to compensate for the GTO switching losses and coupling transformer resistive and core losses. The voltage regulation leads to an increase in the transmitted real power to the load bus B3 with PL=0.2875pu, due to the reactive power compensation, the transmitted reactive power also decreases to QL=0.13pu. Fig. 8(g) shows the resolved d-q STATCOM current components. The STATCOM current is totally a reactive current.

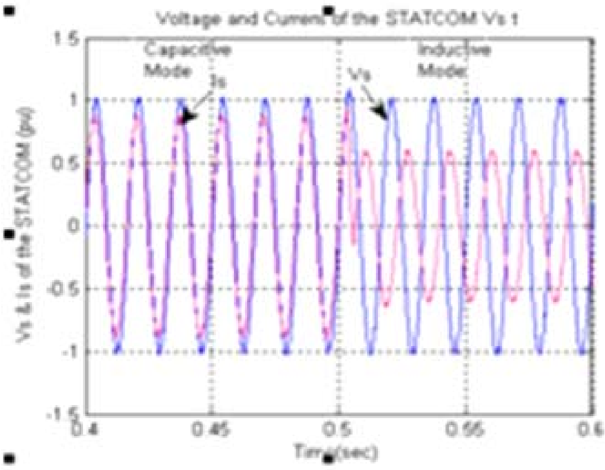
Step 2) t=0.15s—at this time, the second inductive load 2 with P=0.7pu and Q=0.5pu (at rated voltage) is added to the ac power system at bus B3; therefore, more dynamic reactive power compensation is still required. The STATCOM small voltage phase displacement angle increases to $\Delta\alpha = -14$.again, and therefore, the dc capacitor voltage increases as shown in Fig. 8(a). The STATCOM injects about 0.51 p.u. of reactive power into the ac network at bus B2 and draws about 0.03 p.u. of real power to compensate the added losses. The regulated bus voltage is now about 1.0666 p.u. The STATCOM d -axis current temporarily increases in order to charge the dc capacitor.

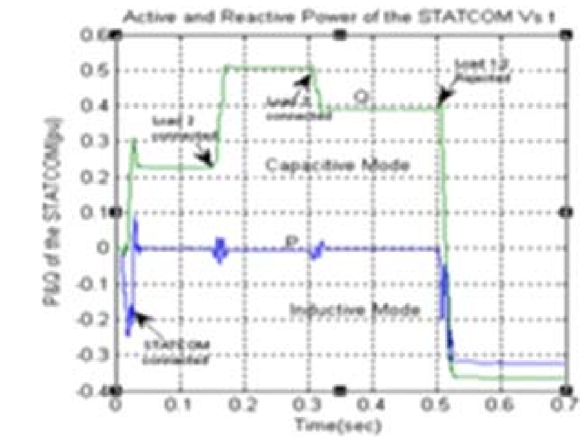
Step 3) t=0.3s—the capacitive load 3 with P=0.6pu and Q=0.4pu (at rated voltage) is now added to the power system at bus B3. The capacitive load has a compensative effect so the STATCOM inject less reactive power into the ac system at bus B2. The injected reactive power is decreased by reducing the dc capacitor voltage, with $\Delta\alpha = -12$, this in turn leads to a decrease in the converter voltage drop. The regulated bus voltage is 1.0678pu, while the STATCOM injects 0.4645 p.u. of the reactive power into the system and draws only 0.01 p.u. real power.

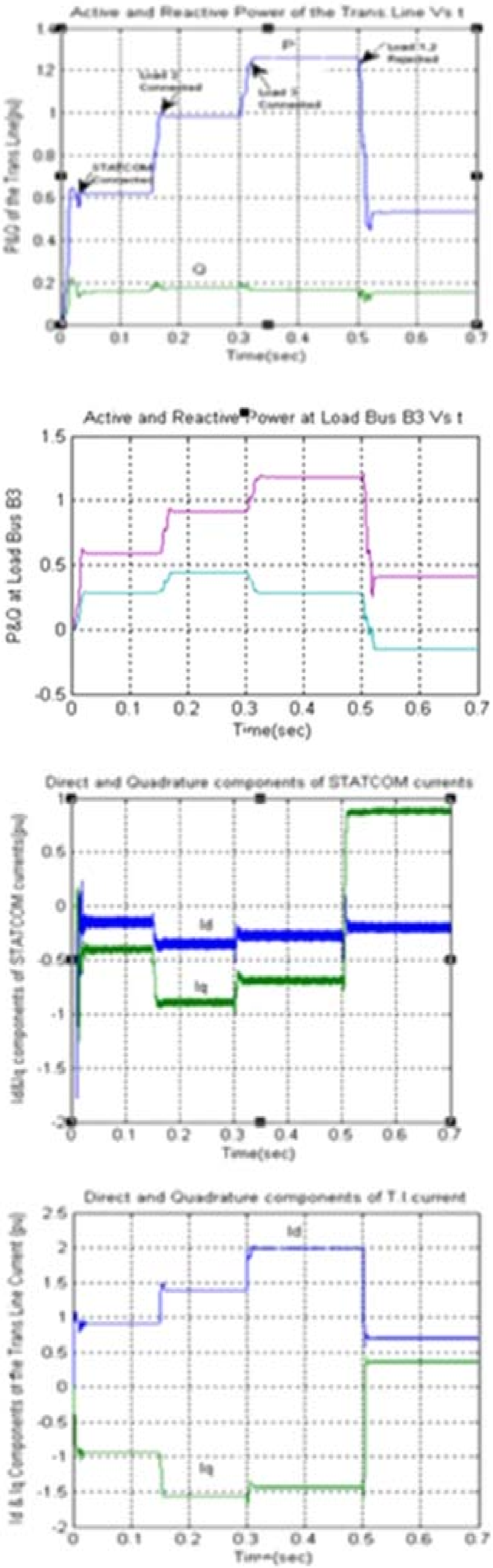
Step 4) t=0.5s—at this time, both loads 1 and 2 are removed from bus B3, which is severe load rejection, and only the capacitive load 3 remains connected at bus B3. Due to this capacitive load, the STATCOM operates in inductive mode to regulate the resultant overvoltage at bus B2 as shown in fig.(i),(j). The STATCOM voltage leads the bus voltage.











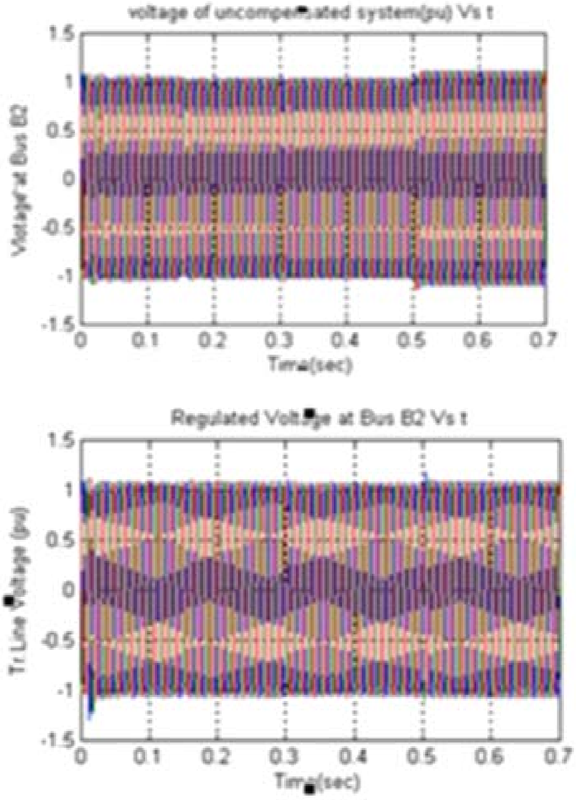


Fig.8 (a - j). Simulation results of the STATCOM Operation

As a result, the dc capacitor voltage drops with $\Delta\alpha = 8.2$ as shown in the fig. 8(a) and (b). The regulated bus voltage is 1.07 p.u., while the STATCOM draws reactive power from the network (inductive operation) and the q–axis current is positive.The dynamic response of the 48-pulse converter voltage and current and the transition sequence from capacitive mode of operation to inductive mode of operation are shown in fig.(c) with no transient overvoltage appeared, and this transition for operation mode takes a few milliseconds. This smooth transition is due to the novel controller, which is based on the decoupled control strategy and the variation of the capacitor dc voltage. Figs. 8(g) and 8(h) show the direct and quadrature components of STATCOM and transmission line currents respectively to provide the phase displacement and to control the converteroperationmode. Fig(8) shows the active and eactive power excursions with reference to dynamic operation of load1,load2 and load3 at bus B3. The total harmonic distortion THD of the output voltage of converter, which is very small compared with other low pulse model of VSC currently used to investigate FACTS devices.

IV. CONCLUSION

The paper presents a novel full 48-pulse GTO voltage source converter of $\pm 100\ MVAR$ STATCOM model of FACTS devices. The full descriptive digital model connected to 500kv electric grid network is validated for voltage stabilization, reactive compensation and dynamically

power flow control using a novel decoupled current control strategy. The control strategies implement decoupled current control technique to ensure fast controllability, minimum oscillatory behavior, and minimum inherent phase locked loop time delay as well as system instability reduced impact due to a weak interconnected ac system.

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